Morphometry of submarine mounds in the lower slope of the Canary continental margin (W of Canary Islands): A DEM – based analysis

Morfometría de montículos submarinos del talud inferior del margen continental canario (O de las Islas Canarias): Análisis basado en un MDT

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Abstract: We present a morphometric analysis of 41 mounded edifices located on the seafloor to the west of Canary Islands, using a 150 m resolution DEM and very high-resolution seismic profiles. In order to carry out morphometric computation a set of variables (slope, size and shape) were calculated using ArcGIS Analyst tools. A mapping cluster has been generated using Grouping Analyst ArcGIS Statistics toolset where seven differents morphometric groups have been distinguished. Four main types of edifice shapes have been identified within the seven morphometric groups. The first type is a single giant dome elevation that can be considered as an outlier mound. The second type is the most frequent and can be considered as the standard type mound on the Canary continental slope due to its intermediate morphology. They show extrusive seismic characteristics in seismic profiles. The third type is morphologically derived from type 2, representing steeper and higher mounds related with extrusive processes whereas the fourth type represents smoother and flatter mounds related to faulting. This study shows that an elaborated geomorphometry resolves between types of extrusive edifices from those under tectonic conditions.

Keywords: *submarine mounds, morphometry, digital elevation models (DEMs), Canary continental slope*

1. INTRODUCTION

Use of digital elevation models (DEMs) for quantitative and qualitative description of landscape is the focus of the relatively new discipline of geomorphometry (Pike *et al.*, 2008). This interdisciplinary science describes, analyses and measures the morphology of the Earth surface. Its application to submarine environments had been infrequent but has become increasingly widespread despite that makes problematic the application of traditional geomorphometric techniques.

First, in comparison to terrestrial landscapes, submarine topographies are generally smoother and the changes in elevation occur over more extensive areas. Secondly, whereas there is no possibility of ground-truthing as in the subaerial DEMs, the study of quantitative seafloor features presents a greater challenge due to observations and sampling are inherently more difficult. Thirdly, the resolution of data sets is also bound to change with depth and the outcomes of geomorphometric techniques depend very much on data resolution (Pike, 2000).

In this work we adapt geomorphometric techniques to the submarine environment for the study of the morphological features of submarine small mounded reliefs based on DEM analysis from the western continental slope of the Canary Islands. The morphological study of mound features can offer a valuable knowledge about their processes and their underlying causes, i.e. tectonic/structural setting, magma flux and eruptive style (Mitchell, 2001).

The objectives of this study are (1) to adapt geomorphometric techniques established for the improved quantitative analysis of submarine elevation data and (2) to test the applicability of this methodology by applying it to the morphological interpretation of the submarine processes.

2. MATERIAL AND METHODS

Acoustic dataset has been acquired during several oceanographic cruises using multibeam echosounder (Kongsberg-Simrad EM-120 and Atlas Hydrosweep-DS) yielding a bathymetric DEM of 150 m spatial resolution. This is the best DEM available for the entire area. Very high-resolution parametric profiles (HRPP) (TOPAS PS18 and Parasound P-35) were simultaneously collected.

2.1 Systematic methodology for the extraction of edifice contour and morphometric variables

The used methodology is based on Grosse *et al.* (2012) which combines profile curvature and slope angle in a single boundary delimitation layer (BDL) using ArcGIS Analyst tools. The BDL is used to trace the contour searching around the edifices and their summits (Fig. 1). The edifice boundary is used to directly compute size variables as: (1) Basal and summit area (*Ba* and *Sa*), (2) Major basal and summit axis (*MBax* and *MSax*) and (3) Perimeter (*P*). Some size variables as (4) Height relief (*H*) and (5) Volume edifice (*V*) have been measured as the absolute difference between the summit and basal relief point or surface of the selected edifice outline, respectively. Other morphological size variables as (6) Flatness (*f* = *MBax/MSax*) and (7) Sigma Value (*SV* = 2 x H / (*MBax–MSax*) (Das *et al*., 2007) have been calculated. Slope variable (8) is straightly computed from the DEM using also ArcGIS Analyst tools. The shape of the edifices are characterized by (9) Ellipticity Index (*EI* = Π x (*MBax*)^2/*Ba*), which quantifies edifice elongation and (10) Irregularity Index (II = (*P*/2 x *Ba) x (√Ba/Π*)-1) which quantifies edifice complexity (*II*) (for details see Grosse *et al*.,2012).

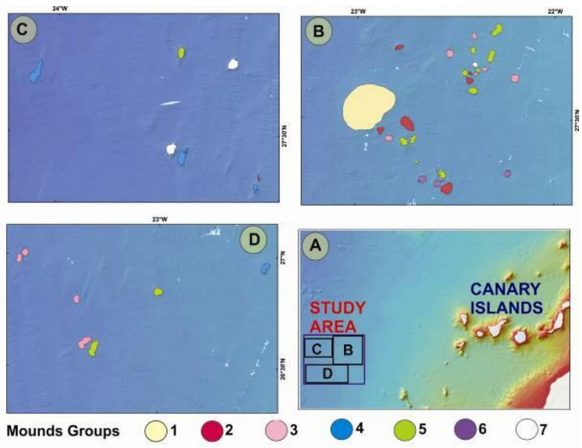

Fig. 1. Spatial distribution of mounds classified in seven geomorphometric groups. A) Study area map where the 41 edifice outlines are displayed; B, C, D) Location of the study area in the Canary continental slope.

2.2 Grouping analyst tool

Once all those measurements were realized for each edifice we used "Grouping analyst" ArcGis Statistics toolset. It performs a classification procedure that tries to find natural clusters in the data sets. Checking the optimal groups for the specified variables calculated may be evaluated with a pseudo-F statistic graph which determinate the most effective number of groups. Given the optimal number of groups to create it will look for a solution where all the features within each group are as similar as possible, and all the groups themselves are as different as possible. Feature similarity is based on the set of morphometric variables that we have specified for the Analysis Fields. A mapping cluster based on K-means algorithm type (non spatial constraint) has been generated (Fig. 1). Summary statistics present calculated R^2 values from 0.99 for *V* and *Ba*, higher than 0.80 for *II*, *S*, *P* and *H* and between 0.77 to 0.67 for *SV*, *EI* and *f*.

3. RESULTS

According to the mapping clusters seven different morphometric groups are able to be distinguished based on the relationships between size, slope, and shape variables.

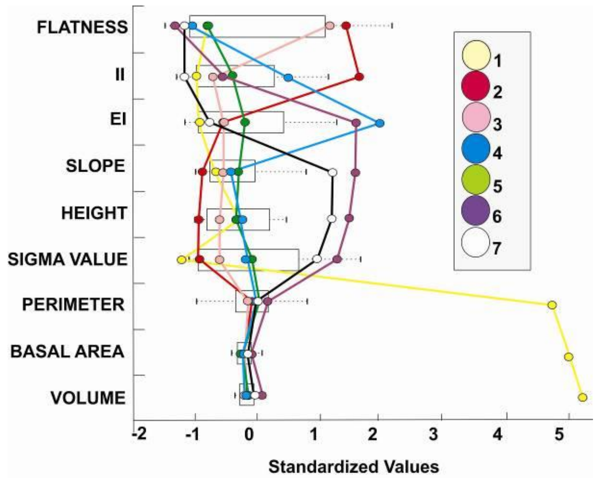

Fig. 2. Parallel box plot graph showing the relationships between the groups and the featured variables within them.

The parallel box plot summarizes the relationships between both, the groups and the variables within them. Group 1 is clearly distinguished by its extremely higher values of the volume, area and perimeter. Group 5 can be defined as standard mound due to do not show any maximum either minimum value in the featured variables. Group 4 is similar to Group 5 but stands apart in shape variables, mainly in *EI* values. Group 2 and 3 are very similar but differ in their *II* values due to Group 2 has the highest values of edifice complexity. Group 6 and 7 are also very similar between them but Group 6 has highest values of each variable except for *f* value and Group 7 present low values of *II*.

3.1 Group 1 (G1)

This group is represented by a unique elevation. This mound is dominated by size variables and can be differenciated from the other due to its giant volume, area and perimeter values. It has low *EI* of 1.51 and *II* of 1.21. It reaches a maximum high of 77 m from the seafloor showing low slope values in the flanks (<4°) with a *V* of 11 km^3, 78 km of *P* and 443 km^2 of *Ba*. The summit present several small peaked zones presenting intermediate *f* values of 0.164 with the lowest SV of 0.008. This mound is located at the central zone of the study area (Fig. 1B).

3.2 Group 2 (G2)

This group contains 7 mounds. They present the highest *f* value of 0.57 and *II* between 2.22-2.68 together with the lowest *H* (10-32 m) and *S* (1.79°- 3°) and small *SV* (0.009-0.035) values. They present different sizes with the widest distributive range of basal area between 1.8-40 km^2 showing perimeters of 6-24 km (14 km as mean value) and intermediate values of *EI* (1.26-3.15). It is dominated by size and shape variables, mainly by *f* and *II* therefore do not reach significantly from seafloor showing irregular shapes in most of cases. Spatially are widely located at the central zone of the study area (Fig. 1B).

3.3 Group 3 (G3)

This group includes 9 mounds that are characterized by their high flatness values. They are very similar to G2 in terms of *S* (around 6°) and BA range (2-22 km^2) but with higher heights, reaching a maximum of 53 m and showing smaller and more regular perimeters (around 11 km as mean value, *II* of 1.31-1.63 and similar *EI* of 1.21-3.08). They are shown grouped in two different zones, the northeastern (Fig. 1B) and southwestern zones of the study area (Fig. 1D).

3.4 Group 4 (G4)

This group contains 4 mounds that present the most complex and elliptical shapes. These mounds have moderate *SV* (0.03-0.09) but low *f* values (0.06-0.17). They are multipeaked mounds forming by elongated ridges. Shape variables dominate their character, presenting highest values of *II* (> 5.3) and the maximum values of *EI* (4.3-5.3). They are mainly displayed at the western zone of the study area (Figs. 1C and 1D).

3.5 Group 5 (G5)

This group represents 13 mounds which present medium values of each analyzed variable, do not showing any extreme value. They have *SV* of 0.007-0.07, *f* of 0.03-0.25 and *EI* values between 1.43-3.21. They present variable slope angle (6°-12°), height up to 100 m and low *II* near 1 showing subcircular to elongated shapes. They present small values of *Ba* (2-18 km^2) and *P* (2-15 km) with intermediate volume of 0.19 km^3 as mean value. These mounds are the most frequent and occur mainly clustered in the central and northeast part of study area (Figs. 1B and1D).

3.6 Group 6 (G6)

This group is represented by the three highest mounds. They are dominated by size (*H* and *SV*) and slope values due to perform the main edifices in the whole study area. They present highest *S* values of and 19°-24°, *H* between 195-243 m and *SV* of 0.135-0.145. These mounds present subcircular shapes (*II* about 1-1.2) but with complex shapes with distal appendices that generate high *EI* values of 1.57-3.95. Their summits are single steep peaked showing small *f* values (0.03-0.11). In this group *V* is the most significant due to their high *S* and *H* values. They are mainly located at eastwards of the study area (Fig. 1B).

3.7 Group 7 (G7)

The last group includes two mounds, which present also high values of *H* (100-150 m), *S* (12.5°-17°) and *SV* (0.093-0.097) but do not show complex either elliptic shapes. They present the lowest and widest distributive range for *EI* of 1.37-2.3 and uniform *II* of 1.1, showing near circular shape. They are located in the western area of the study area (Fig. 1C).

4. DISCUSSION AND CONCLUSION

The relationship between shape, slope and size variables has resolved in seven different morphological groups where four main types of mounded edifice (Fig. 3) can be recognized based purely on the morphometric data: (1) unique giant dome edifice (G1); (2) 13 morphological standard mounds which present intermediate values in each variable (G5) together with 4 mounds (G4) which stand out from G5 due to higher shape values, (3) 5 steeper and higher edifices than G5 (G6-G7) and (4) 17 smoother, smaller and flatted edifices than G5 (G2-G3).

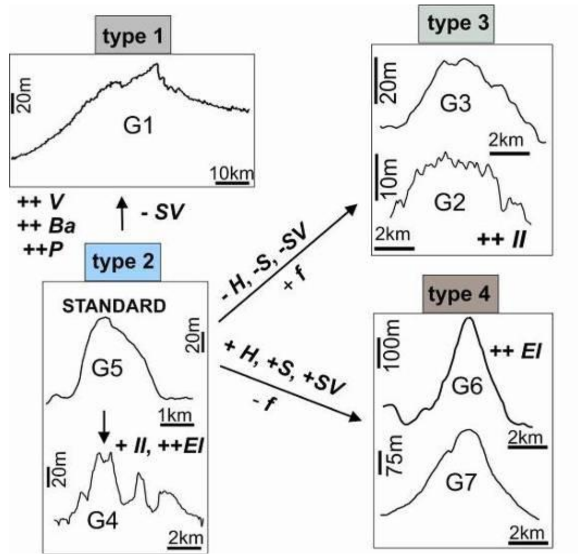

Fig. 3. Schematic morphometric model indicating the main four types of mound shapes in the study area.

The first type is a single bulge that is characterized by the widest mound observed in the area. Based on HRPP (Fig. 4) it appears clearly affected by fracture zones that may be related with a regional outcropped dome structure or possibly with an underneath volcanic system despite there are not seismic evidences in HRPP.

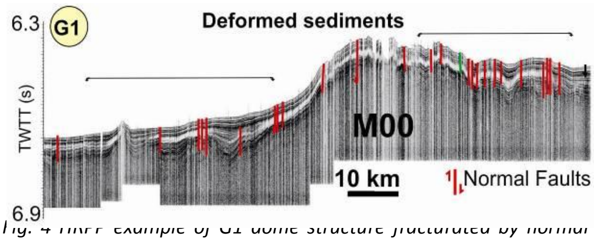

Fig. 4 HRPP example of G1 dome structure fracturated by normal faults.

The second type is not dominated by any morphometric variable. G5 mounds always present intermediate values and can be considered as the standard on the Canary continental slope. This type encloses G4 and G5 mounds and they can be differentiated due to G4 present highest values in *EI* and *II* probably in relation with multiple extrusive events along adjacent fissures (Fig. 5B) whereas G5 may represent central vent-controlled mounds (Fig. 5A).

The third type of edifices is dominated by high *S*, *H* and *SV* together with low *f* values. This type contains G6 and G7 mounds that have been differentiated between them due to G6 present higher *EI* than G7. Based on HRPP this fact may be possibly due to G6 represents faster or higher extrusive events than G7, possibly depending on the eruption rate, conduit geometry or pre-existing topography (Das *et al*., 2007) (Figs. 5B-C).

The extrusive origin of these two types of mounds is further supported by the presence of disturbed upwards and downwards reflectors and deeper chimneys of low amplitude (Fig. 5).

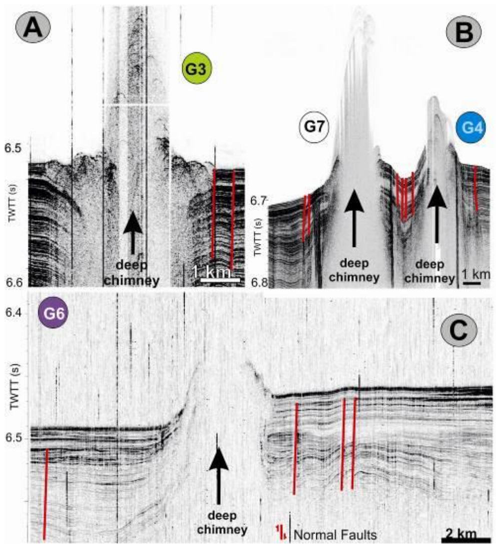

Fig. 5. HRPP examples of extrusive edifices. Internal deep chimneys is shown together with lateral normal faults.

The fourth type is dominated by mounds with highest *f* together with low *S*, *H* and *SV*. This relationship concurs with the observed for Das *et al*. (2007) where *f* is inversely proportional to the height. In the HRP profiles these mounds are the result of sedimentary deformation caused by faulting (Fig. 6) due to regional stress field may influence the formation of mounds (Das *et al*., 2007). The variation between G2 and G3 is defined by the higher *II* values of G2. This group is strong tectonic affected by recent normal faults (Fig. 6A). Differences in the irregularity can be influenced by local tectonic setting and thickness of the sediment cover (Grosse *et al*., 2012).

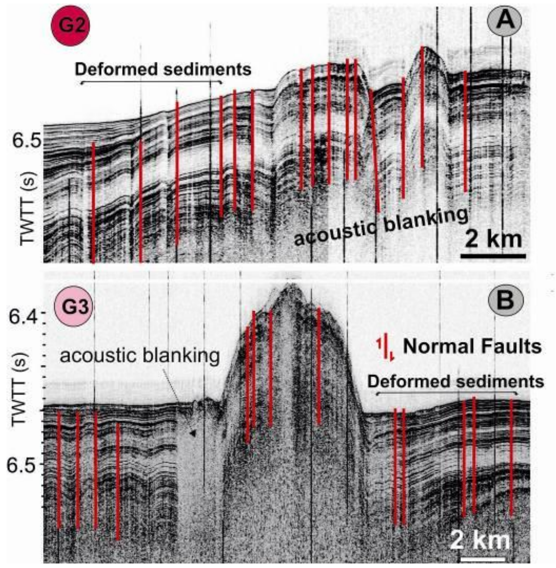

Fig. 6 HRPP examples of G2 and G3 tectonic bulges. These structures are shown fracturated by normal faults.

This study shows that an elaborated geomorphometric classification based on size, shape and slope variables resolves between types of extrusive edifices from those under tectonic conditions. Based on the result of the present geomorphometric analysis, variables as *SV*, *f*, *EI* and *II* provide a new fairly good idea about the constructive processes acting on submarine mounds and their resulting morphologies.

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